

# Optimizing Channel Access for Event-Driven Wireless Sensor Networks: Analysis and Enhancements

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**Abstract**—We study the problem of medium access control in domain of event-driven wireless sensor networks (WSNs) [17]. In this kind of WSN, sensor nodes send data to sink node only when an event occurs in the monitoring area. The nodes in this kind of WSNs encounter correlated traffic as a subset of nodes start sending data by sensing a common event simultaneously. We wish to rethink of medium access control (MAC) for this type of traffic characteristics. For WSNs, many existing MAC protocols utilize the basic CSMA/CA strategy such as IEEE 802.11 Binary Exponential Backoff (BEB) algorithm to handle the collisions among packets when more than one node need to access the channel. We show that this BEB algorithm does not work well without incurring access delay or performance degradation due to increased number of collisions and retransmissions when nodes encounter correlated traffic. Based on above observations in mind, We present a Adaptive Random Backoff (ARB) algorithm that is capable of mitigating the impact of correlated traffic and capable of minimizing the chance of collisions. ARB is based on minor modifications of BEB. We show using numerical analysis that our proposals improve the channel access in terms of latency, throughput, and frame dropping probability as compared with IEEE 802.11 DCF. Simulations using NS-2 network simulator are conducted to validate the analytical results.

**Index Terms**—CSMA/CA, IEEE 802.11, Backoff algorithm, performance analysis, Wireless Sensor Network.

## I. INTRODUCTION

The recent developments in wireless sensor networks have enabled low cost, low power sensor nodes which are capable of sensing, computing and transmitting sensory data in environments such as surveillance fields, smart homes, offices and intelligent transportation systems. These sensor nodes cooperatively monitor physical and environmental conditions such as temperature, sound, vibration, and pressure etc. WSNs are also used for critical applications in highly dynamic and hostile environments. Therefore, they must adapt to failure of nodes and loss of connectivity.

The sensor networks are emerging area of mobile ad-hoc network that presents novel networking issues because of their different application requirements, limited resources capabilities and functionalities, small packet size, and dynamic multi-hop technologies. The Medium Access Control (MAC) is an important mechanism to share wireless communication channel by resolving the issues of collisions thus leading to successful transmission of packets. Many MAC protocols have been designed for traditional wireless networks [3]. While these protocols are well suited for traditional wireless

networks, they are not adequate for wireless sensor networks due to different nature of traffic characteristics and application behavior. The primary function of a sensor network is to sample sensory information from its vicinity such as temperature, light, and send this data to the base station node. The base station node mostly forwards all the data wire-line or an independent wireless network to control center. The sensor nodes in network operate as a collective structure which makes this network different than traditional ad-hoc networks. Due to dependency on sensor for generating data, the traffic characteristics are variable and correlated. Mostly they change little over long period of time and on other hand can be very intense for short period of time. This correlated traffic is characteristics of densely deployed wireless sensor network applications. For example, in room monitoring application where a fire in a room of a building triggers a number of nodes attached with temperature sensors to begin reporting a common event. These all nodes, simultaneously become active and transmit packets. This behavior causes the nodes to operate in spatially-correlated contention where multiple nodes of same neighborhood sense a common event at same time [16], [17].

We wish to rethink of CSMA based MAC design for this types of traffic characteristics in mind especially for event-driven based sensor network applications. Tay, Jamieson, and Balakrishnan [3] have defined characteristics for event-driven sensor network applications as follows.

- An event-driven based sensor network encounters spatially-correlated contention, once an event occurs into a particular region/zone of monitored area. The multiple nodes of same neighborhood sense it and send data to report it to the base station node. As a result, a synchronized burst of transmissions happens.
- In many applications, all the packets need not be treated as equally important. It is enough that some nodes out of all, are successful in transmitting the data.
- The number of nodes getting activated by an event in a particular region changes with time. For example, when a target enters into a sensor field, the number of active sensing nodes could become large very quickly.

In these types of traffic patterns, channel access delay and system throughput are the performance limiting factor when

number of contending nodes are large that are activated by means of occurring an event into a specific zone of sensor field. Our goal is to minimize the channel access delay and improve the system throughput in event-driven based sensor network applications.

These characteristics pose a challenge in design of MAC protocol for event-driven based wireless sensor networks. Tay, Jamieson, and Balakrishnan [16] have also proposed a solution to this problem using fixed contention window size of 32 slots with non-uniform probability distribution. This is contention-based protocol, (named as SIFT) to allow first  $R$  winners of contention to send the reports to base station when  $N$  nodes sense an event and contend to transmit simultaneously. It has been designed for sensor network applications when spatially-correlated contention occurs by sensory measurements of an event that triggers many sensor nodes in event-driven scenario, where multiple sensor nodes detect an event to send data to the sink node through multiple-hop communication. The basic idea in SIFT protocol is to randomly selecting contention slots using non-uniform probability distribution within fixed sized contention window rather than using variable contention window size as used in many traditional MAC protocols. Simulation results show that SIFT outperforms 802.11 DCF in term of report latency by a factor of 7 [16]. One drawback of SIFT is that it degrades in performance when number of contending nodes exceeds 512. In other words, as the number of nodes reporting an event become larger than 512, slots get picked by multiple nodes, resulting in collisions. Authors argued that traditional carrier-sense multiple access (CSMA) strategies like IEEE 802.11 DCF is not suitable in this problem domain, and the larger value of contention window size is not always necessary for sensor network applications since traffic is mostly very low and becomes intense only when any activity is observed in the environment.

To mitigate the impact of spatially-correlated contention among the active nodes on the network performance, particularly observed into event-driven based sensor applications [16], we proposed a new adaptive and predictable algorithm, called adaptive random backoff (ARB), that is based on minor modifications of the IEEE 802.11 binary exponential backoff (BEB). The motivation of ARB is the enhancement of BEB performance for correlated traffic generated from multiple nodes of same neighborhood when these nodes sense an event in a event-driven scenario. The rest of paper is organized as follows: Section II illustrates the behavior of IEEE 802.11 DCF. Section III presents the overview of related work. Section IV describes the details of our proposed algorithm ARB. Section V evaluates the efficiency of ARB through simulation experiments. Finally, conclusions and future work are presented in section VI.

## II. IEEE 802.11 – WHAT GOES WRONG

In this section we present analysis of IEEE 802.11 DCF method using analytical model given by [2]. We will show that IEEE 802.11 DCF can cause latency problem and degrade the performance for event-driven WSN.

The IEEE 802.11 standard [1] is designed to support communication among nodes in ad-hoc peer-to-peer configuration as well as designation access point in infrastructure mode of operation. Traditionally, nodes in wireless adhoc networks, communicate with each other as peers using multi-hop. While in WSNs, irrespective of multi-hop or single-hop, all the nodes will usually communicate with a base station node. In the 802.11 protocol, two mechanisms have been defined for medium access. The fundamental mechanism called, the distributed co-ordination function (DCF), is a random access scheme based on the Carrier sense multiple access with collision avoidance (CSMA/CA) protocol. Another mechanism is defined as an optional point coordination function (PCF) which is a centralized MAC protocol for supporting collision-free, time bounded services. DCF describes two techniques for packet transmission. The default scheme is a two way hand shaking mechanism called the basic access scheme. Another scheme called the Request to send/Clear to send (RTS/CTS) is a four way hand shaking mechanism defined by the standard. It has been specially formulated to encounter the hidden node/exposed node problem. In basic access scheme, a node, with a packet to transmit, monitors the channel activity. If the channel is free for a period of time equal to Distributed Inter Frame Space (DIFS), the node performs transmission as shown in Fig.1(a). If the channel is sensed busy, either immediately, or during the DIFS the backoff procedure is activated. The node again continues to monitor the channel till it is sensed idle for a DIFS period of time. At this point, the node generates a random number between 0 and CW (contention window) and use it to initialize the counter to perform backoff and starts the countdown procedure. This counter is decremented by one for every idle time slot sensed by node. When it reaches to zero, node transmits the packet immediately as shown in Fig.1(b). Also a node needs to wait for a random back-off interval between two of its consecutive successful packet transmissions by the same node. Initially (i.e. backoff stage 0), backoff is chosen in between zero to minimum value of contention window ( $W_{min}$ ). After each unsuccessful transmission due to collisions, backoff stage is incremented by one and contention window (CW) doubles its value till it reaches to maximum value of CW ( $W_{max}$ ). According to IEEE 802.11 standard, size

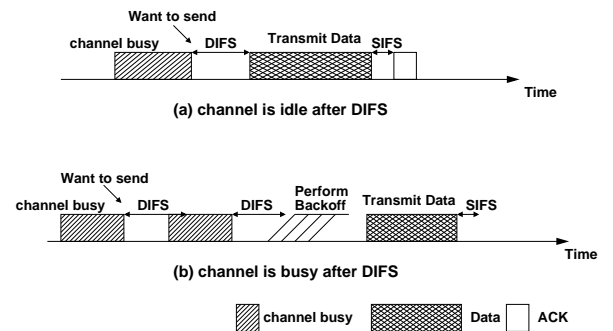


Fig. 1. CSMA/CA mechanism illustration

of contention window will not change when retransmission limit reaches a threshold value, we call it backoff order, denoted by  $m$ . When transmission is successful, the backoff stage will start with initial value of 0 and initial CW will reset to  $W_{min}$ , regardless of network traffic conditions. The DCF method tends to work well when number of contending nodes is few. As discussed in previous section, it does not efficiently handle the spatially-correlated contention occurring in event-driven WSN. To better understand the performance of DCF, we reproduce the numerical results using analytical model proposed in [2] and observe the behavior of protocol under full load conditions.

We observe that, the conditional collision probability increases with the increase in the number of nodes which causes a reduction in the system throughput. On the other hand for a single node throughput falls because of minimum contention window size, which introduces unnecessary idle slots. Based on observation using analytical model, followings are some of the drawbacks of the basic access mechanism of IEEE 802.11 DCF:

- Although, DCF tries to avoid frame collision by using the binary exponential backoff (BEB) algorithm, still it can not avoid the inevitable retransmission of frames when the number of competing nodes is fairly large.
- As the waiting time of a node grows exponentially with the number of frame retransmissions, it becomes mandatory for DCF to bound the number of retransmissions to a smaller number.
- Intuitively we can say that, as contention window size increases, the average backoff timer value chosen before every transmission attempt, increases. Thus, on an average, a node will be able to transmit the packet only after a longer period of time.
- If the packet at the head of the buffer gets backlogged for a longer period of time due to consecutive failures in retransmitting the packet, the remaining packets in the buffer will also have to suffer a larger delay. Many a times, due to this phenomena, the buffer becomes full with packets and then the future incoming packets will be dropped till the time the severely backlogged packet at the head of the queue gets successfully transmitted.

In [2], an approximate solution relating the transmission probability  $\tau$  with the number of nodes  $N$  is derived, which maximizes the system throughput. We can say that  $\tau$  depends only on the system parameters backoff order  $m$ , contention window CW, and the network size  $N$ . Hence, the way to achieve optimal performance is to employ adaptive techniques to tune the values of  $m$  and CW (and consequently  $\tau$ ) on the basis of the estimated value of  $N$ . In event-driven wireless sensor network, network congestion becomes severe when an event is detected by number of sensors close to it. This subset of nodes suddenly get activated to report the event via multi-hop transmission to a distant sink node or base station node. This type of traffic characteristics leads to synchronized transmissions from the active sensors at the same time. Thus

population size of contending sensors that are reporting an event at a time increases significantly. Hence, collision ratio is higher on detection of an event in the environment.

The BEB algorithm used in IEEE 802.11 DCF is not suitable for event-driven WSN. First, Since BEB algorithm doubles its CW size after each collision, when active population of nodes is large, it takes time to adapt to right value of CW size after significant amount of collisions. It will happen when several nodes observe an event around it the same time. Second, contention window size is reset to its initial value ( $W_{min}$ ) after each successful transmission. This does not consider current status backlogged nodes indicated by recently used CW. Larger CW is indication of large number of contending nodes which may not settle down immediately in case of event-driven applications. Finally, at the time of event occurrence, if contention window of the node is already large, and only some sensor nodes get chance to report that event, then delivery latency of the event is fairly high due to large CW size.

### III. RELATED WORK

In WSN, the research on MAC protocol design has been focused mainly on energy-latency trade-offs. SMAC [6] is designed to save the energy by using listen and sleep periodically with collision avoidance facilities of IEEE 802.11 standard. S-MAC uses synchronization mechanism to form virtual clusters of sleep/wakeup schedule to avoid overhearing problem. Many variants of S-MAC have been proposed to further decrease the energy consumption. These are D-MAC [7], T-MAC [8], DS-MAC [11], P-MAC [12], TEEM [13], DW-MAC [14] etc. These all variants deal with major source of energy wastage such as idle-listening, overhearing and collisions problems. B-MAC [15] is low power listening mechanism, best suitable for low data rate wireless sensor networks. Similar to S-MAC, and T-MAC, B-MAC also uses periodic ON and OFF of radio transceiver. However, it is unsynchronized duty cycle protocol. In order to transmit the packets, nodes sent long preamble before actual data transmission. These MAC protocols have been designed for general sensor network applications where latency is not considered as critical parameter.

In this paper, we are considering contention-based protocol for event-driven WSN where latency is an important parameter. Many existing MAC protocols (e.g. S-MAC, T-MAC, P-MAC etc.) utilize the IEEE 802.11 DCF mechanism in order to handle hidden terminal, exposed terminal, and network congestion problems. As discussed in previous section, performance of IEEE 802.11 DCF is weak when network traffic is frequent or correlated depending on nodes' interaction with physical environment. As a result, protocols based on IEEE 802.11 are not suitable for event-driven WSN. In IEEE 802.11, backoff time is chosen randomly in the range of  $[0, CW)$ . The node waits for the chosen random number of vacant slots before transmitting. If two nodes contend to access the channel at the same time, and both find free channel for DIFS time, both of them transmit resulting in collision. After collision, each colliding node choose random number

of vacant slots to wait from the range  $[0, CW)$ . Here  $CW$  for a node is  $2^i \times W_{min}$ , where  $i^{th}$  collisions has been suffered for a packet transmission. The node which has backoff time corresponding to lower slot number gets the chance to access the channel while other nodes with higher slot number wait for channel access. Backoff time is random variable and can be a large value depending on range from which random number is selected. For event-driven sensor network applications, sometimes less number of nodes becomes active to report a common event, or sometimes larger number of nodes will report an event. So according to active population of nodes reporting an event, a backoff algorithm must set right value of contention window size.

For event-driven sensor network applications, very little work has been published in literature. The CC-MAC was proposed by Vuran and Akyldiz [16] for event-driven WSN. They have explored spatial correlation in wireless sensor networks. In CC-MAC, Iterative Node Selection (INS) algorithm was proposed to calculate correlation radius ( $r_{corr}$ ) based on correlation model. Only one node is allowed to transmit event information within a correlation radius. In this way, CC-MAC suppresses the transmissions by other nodes within same correlation radius. This single node is referred as representative node selected by CSMA mechanism during each transmission within  $r_{corr}$  radius. In first contention phase, all nodes within  $r_{corr}$  radius contend to access the channel like in any other contention based protocol. As a result, only node winning the contention is selected as representative node while other nodes turn to sleep. In CC-MAC, there is no control on selection of representative node to further saving the energy. It is unpredictable that which node will win the contention. SIFT MAC [17] is another protocol designed for event-driven WSN. The objective of SIFT MAC protocol is to minimize the latency when spatially-correlated contention occurs in a monitored area. Jamieson et. al [17] had argued that only  $R$  nodes out of  $N$  nodes that report to a common event are sufficient to be successful to transmit the event information to the sink node. SIFT MAC uses non-uniform geometric distribution to choose slot number for picking up a slot for transmission within fixed-size contention window (32 slots).

#### IV. DETAILS OF ADAPTIVE RANDOM BACKOFF (ARB)

Since each event triggers a large number of nodes for sensing and transmission, it is prudent to have a initial window (say  $W_{est}$ ) being estimated based on past experience. Thus chance of collision are reduced to a greater extent. Further  $CW$  can be adapted when collisions happen. When a node's transmission collides  $i^{th}$  times  $CW$  can be increased to  $2^i W + W_{est}$ . This provides for desired adaptability. Here  $W$  is increment in  $CW$  after first collision. The  $CW$  when packet is successfully transmitted can also be used to update  $W_{est}$  for use in future transmissions. In this section, we present ARB scheme that is based on minor modifications of BEB. Unlike BEB, our ARB protocol focuses on adjusting the contention window to achieve higher throughput and better channel access delay for event-driven WSN applications.

#### A. Assumptions & model used

In the event-driven WSNs, we assume that network consisting of  $N$  sensor nodes, is deployed with a sink node one hop away from sensor nodes. Based on Bianchi's model [2] and ZA's model [4], we analyze the performance analysis of our modified protocol in order to optimize the channel access specially for event-driven wireless sensor networks. We are interested in specific area inside sensor field where an event is generated by means of some activities for example detection of an intrusion or sudden change of temperature in case of fire etc. When an event occurs significant number of sensor nodes closer to it get activated and each triggered node has a packet to transmit to sink node independently using MAC.

Following [2], [5], for a given node, let  $w(t)$  the stochastic process that represents  $i^{th}$  backoff stage in the range  $i = 0, 1, 2, \dots, i = L$ , where  $L$  is maximum retransmission limit (retry limit) and  $b(t)$  be the stochastic process that represents  $k^{th}$  backoff counter in the range  $k = 0, 1, 2, \dots, W_i - 1$ , where  $W_i$  is given by  $\lceil 2^i \times W_{min} \rceil$ . Therefore, the system can be modeled as a Markov chain model  $\{w(t), b(t)\}$  representing the state of each node  $\{i, k\}$ . This model has assumption that each packet collides with constant and independent probability  $p$  during each transmission attempt irrespective of number of retransmission suffered, it has been shown in [2], [5] that:

1) the probability  $p$  can be expressed as :

$$p = 1 - (1 - \tau)^{N-1} \quad (1)$$

2) the probability  $\tau$  can be expressed as:

$$\tau = \sum_{i=0}^m b_{i,0} = b_{0,0} \frac{1 - p^{L+1}}{1 - p} \quad (2)$$

where  $b_{0,0}$  is given by Eq. (3).

$$b_{0,0} = \frac{1}{\sum_{i=0}^L \left[ 1 + \frac{1}{1-p} \sum_{k=1}^{W_i-1} \frac{W_i-k}{W_i} \right] p^i} \quad (3)$$

According to Bianchi's model [2], the  $\tau$  is known as attempt probability. Bianchi has used a two-dimensional model to obtain the expression with no retransmission limit. Later, the limit for maximum retransmission was addressed in [5]. The Eq. (1) and Eq. (2) form a system of two non-linear equations that has unique solution and can be solved numerically for values of  $p$  and  $\tau$ .

#### B. Proposed ARB algorithm for Event-Driven Scenario

From analysis in [2], BEB algorithm is main key factor that influences the system efficiency. In IEEE 802.11 Binary Exponential Backoff (BEB) algorithm, size of contention window ( $CW$ ) is doubled on each unsuccessful transmission and reset to initial value of  $CW_{min}$  after each successful transmission, described as Eq. (4). As illustrated in **Algorithm 1**, the Backoff value  $cw$  is randomly selected from the range  $[0, CW]$ , where  $CW_{min} = 2^{i_{min}} - 1$  and  $cw = \text{rand}() \bmod CW_{min}$ , ( $i_{min} = 5$  in 802.11 DCF). The  $CW$  will be double after each unsuccessful transmission attempt and continue to increase until it reaches the upper bound

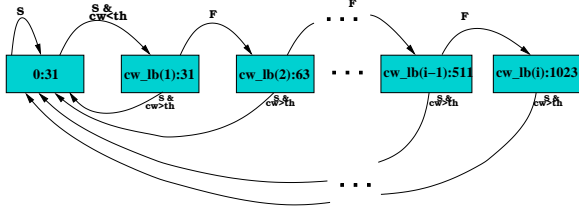


Fig. 2. Proposed ARB algorithm for Event-Driven Scenario

$CW_{max}$ , where  $CW_{max} = 2^{i_{max}} - 1$  (1023 in 802.11 DCF). When retransmission limit reaches a threshold value, denoted as  $m$ , the CW does not increase further. If  $i$  denotes the number of successive failed transmission (due to collision or packet error), the increment in CW explained above can be summarized:

$$W_i = \begin{cases} 2^i \times W_{min} & i \leq m; \\ 2^m \times W_{min} & i > m. \end{cases} \quad (4)$$

In the event-driven WSNs, contention resolution becomes critical due to simultaneous transmission. To mitigate the severe collision into sensing region, it is prudent to have average value of CW (say  $W_{avg}$ ) being estimated based on past experience. The CW when packet is successfully transmitted, can also be used to update  $W_{avg}$  for use in future transmissions. Therefore, the key idea of our ARB method is to predict the  $W_{avg}$  based on current CW after each unsuccessful transmission attempt. Since it is based on minor modifications of BEB algorithm, the backoff value is selected randomly from the contention window. Unlike BEB algorithm, the lower bound of CW for next transmission is updated with  $CW_{avg}$  based on current contention window.

1) *Illustration of ARB*: ARB operates as follows (as shown in Fig.2 and **Algorithm 2**): when a node has a data packet to transmit a  $cw_i$  is selected randomly from  $[0, CW_{min}]$  similar to BEB. Upon a successful data transmission, if  $cw_i$  is less than  $CW_{th}$ <sup>1</sup>, a lower bound of CW for the next  $cw_{i+1}$  selection will be assigned as  $CW_{lb} = \alpha \times CW_{avg}^i$ , where  $CW_{avg}^i = 2 \times cw_i + CW_{avg}^{i-1}$ . In case, the  $cw_i$  is equal to 0,  $CW_{lb}$  is set to default value<sup>2</sup>. Otherwise,  $CW_{lb}$  will be reset to zero. Therefore, the node will set the value of  $cw_{i+1}$  from the range  $[CW_{lb}, CW_{min}]$  for next transmission. If there is a failed transmission, the CW is doubled and the backoff value,  $cw$  is selected from the range  $[CW_{lb} - 1, \min(2^{i_{min} + n_f}, 2^{i_{max}}) - 1]$ , where  $n_f$  is the number of a failed transmission. The CW keeps increasing until it reaches the  $CW_{max}$ .

In this way, the weighted average value of CW is computed dynamically in each unsuccessful transmission attempt and kept unchanged upon successful transmission attempt to use for future transmission. In addition, the collision ratio is higher on detection of an event (explained in previous section). After each successful transmission, BEB algorithm does not consider current status of backlogged nodes indicated by current larger value of CW, it decrements the CW to  $CW_{min}$  immediately.

<sup>1</sup>  $CW_{th}$  is used to reset the lower bound of CW.

<sup>2</sup> Note that the default value of  $CW_{lb}$  is set to 1.

#### Algorithm 1 Binary Exponential Backoff

```

1:  $cw_0 \leftarrow [0, 2^{i_{min}} - 1]$ 
2: for each sending packet  $P_i$  do
3:   if fail in transmitting  $P_i$  then
4:      $CW_{i+1} = 2 \times CW_i$ 
5:   else
6:      $CW_{i+1} = 2 \times CW_{min}$ 
7:   end if
8:   if  $CW_{i+1} > CW_{max}$  then
9:      $CW_{i+1} = CW_{max}$ 
10:  end if
11:   $cw_{i+1} \leftarrow [0, CW_{i+1} - 1]$ 
12: end for

```

#### Algorithm 2 Adaptive Random Backoff For Event-Driven Scenario.

```

1:  $CW_{avg}^0 = 2$ 
2:  $cw_0 \leftarrow [0, 2^{i_{min}} - 1]$ 
3: for each sending packet  $P_{i+1}$  do
4:   if  $cw_i < CW_{th}$  then
5:     if  $cw_i == 0$  then
6:        $CW_{avg}^i = 0$ 
7:     else
8:        $CW_{avg}^i = 2 \times cw_i + CW_{avg}^{i-1}$ 
9:     end if
10:  else
11:     $CW_{avg}^i = 0$ 
12:  end if
13:   $CW_{lb}^{i+1} = \alpha \times CW_{avg}^i$ 
14:   $cw_{i+1} \leftarrow [CW_{lb}^{i+1} - 1, \min(2^{i_{min} + n_f}, 2^{i_{max}}) - 1]$ 
15: end for

```

To reduce the higher collision ratio in the presence of an event, the CW should follow gradually decrease by halving the value on each successful transmission (similar to that in [9], [10]), instead of immediately resetting it to  $CW_{min}$ .

#### C. Performance Evaluation

The Eq. (1), Eq. (2) and Eq. (3) can be rewritten for BEB model and our ARB model as follows:

$$\frac{2(1-p)}{b_{0,0}} = \sum_{i=0}^L [2(1-p)p^i + (W_i - 1)p^i] \quad (5)$$

Where,  $W_i$  is contention window at  $i^{th}$  backoff stage. Then the relationship between transmission Probability  $\tau$  and conditional collision probability  $p$  can be expressed by:

$$\tau = \frac{2(1-p^{L+1})}{\sum_{i=0}^L [2(1-p)p^i + (W_i - 1)p^i]} \quad (6)$$

and

$$p = 1 - (1 - \tau)^{N-1} \quad (7)$$

The performance analysis of BEB model and our ARB model have been carried out by solving the Eq. (6) and Eq. (7) numerically.

1) *Normalized System Throughput*: Let  $P_{tr}$ ,  $P_s$  denote the probability that at least one transmission is holding a given slot time and the probability of successful transmission, given the probability  $P_{tr}$  respectively. So we have

$$P_{tr} = 1 - (1 - \tau)^N \quad (8)$$

$$P_s = \frac{N\tau(1 - \tau)^N}{1 - (1 - \tau)^N} \quad (9)$$

Let  $S$  be the normalized system throughput which is the average payload sized packet transmitted in a slot over the average duration of a slot time, expressed as Eq. (10).

$$S = \frac{E[\text{Payload transmission during a slot time}]}{E[\text{Duration of slot time}]} = \frac{P_s P_{tr} E[P]}{P_s P_{tr} T_s + P_{tr}(1 - P_s)T_c + (1 - P_{tr})T_{id}} \quad (10)$$

where we use same symbols as used in paper [2],  $E[P]$  is average packet payload size,  $T_s$  is average time needed to transmit a packet of size  $E[P]$ ,  $T_{id}$  is duration of idle period in a time slot,  $T_c$  is average time spent in collisions. Let  $T_H$ ,  $T_{E[P]}$ ,  $DIFS$ ,  $SIFS$ ,  $T_{ACK}$  denote the time to transmit the header (including physical header, MAC header), time to transmit a payload of size  $E[P]$ , DIFS time, SIFS time, and the time to transmit an ACK, respectively. For the basic access method, we have

$$T_s^{basic} = DIFS + T_H + T_{E[P]} + \delta + SIFS + T_{ACK} + \delta \quad (11a)$$

$$T_c^{basic} = DIFS + T_H + T_{E[P]} + SIFS + T_{ACK} \quad (11b)$$

Let  $T_{RTS}$ ,  $T_{CTS}$  denote the time to transmit an RTS packet and CTS packet, respectively. For the RTS/CTS access method, we have

$$T_s^{RTS/CTS} = DIFS + T_{RTS} + SIFS + \delta + T_{CTS} + SIFS + \delta + T_H + T_{E[P]} + SIFS + \delta + T_{ACK} + 2\delta \quad (12a)$$

$$T_c^{RTS/CTS} = DIFS + T_{RTS} + SIFS + T_{CTS} \quad (12b)$$

2) *Frame Dropping Probability*: Let  $P_{drop}$  be the probability that a packet is dropped. According to the model, if a collision occurs a packet is dropped only in state  $\{L, 0\}$ . So frame dropping probability  $P_{drop}$  is described as Eq. (13).

$$P_{drop} = p^{L+1} \quad (13)$$

3) *Expected Channel Access Delay*: We define channel access delay as the total time elapsed between instant of time the packet comes in queue and time the packet gets chance of successful transmission. In our model, we obtain the channel access delay by analyzing expected backoff delay, transmission delay, and inter frame spaces (SIFS). The expected backoff delay depends on backoff counter value and duration of which counter freezes. Let total backoff slots be a random variable represented by  $X$  without considering backoff slots

TABLE I  
SYSTEM PARAMETERS FOR MAC AND DSSS PHYS LAYER

SIFS	10 $\mu$ s	DIFS	50 $\mu$ s
Slot time	20 $\mu$ s	PHYS header	192bits
MAC header	224bits	UDP/IP header	320bits
ACK packet	112bits	Data rate	11Mbps
Propagation delay	1 $\mu$ s	Control rate	1Mbps
Retry limit	6	CWmin, CWmax	32, 1024

for which a node freezes counter. The probability that a packet is transmitted successfully after  $i_{th}$  retransmission, is given by  $\frac{p^i(1-p)}{1-p^{L+1}}$  and average backoff slots are  $\sum_{i=0}^L \frac{W_i - 1}{2}$ . So we have

$$E[X] = \sum_{i=0}^L \frac{p^i(1-p)}{1-p^{L+1}} \left( \frac{W_i - 1}{2} \right) \quad (14)$$

where  $E[X]$  is expected backoff delay for only successful transmission. Let  $B$  be random variable representing backoff slots when counter freezes. The probability that  $E[X]$  is decreased when channel is idle, is given by  $(1 - p)$ . So we have

$$E[B] = \frac{E[X]}{(1 - p)} p \quad (15)$$

Let  $E[L_{retry}]$  be expected delay for retransmission (retry). We have

$$E[L_{retry}] = \sum_{i=0}^L \frac{ip^i(1-p)}{1-p^{L+1}} \quad (16)$$

Let  $D$  be a random variable representing transmission delay or packet delay. The  $T_0$  is the time when a node has to wait after its packet collision, and  $T_{ACK\_timeout}$ ,  $T_{CTS\_timeout}$  represent ACK and CTS timeout duration respectively. So we have

$$E[D] = E[X]\delta + E[B]\left[\left(\frac{P_s}{P_{tr}}\right)T_s + \left(\frac{P_{tr} - P_s}{P_{tr}}\right)T_c\right] + E[L_{retry}](T_c + T_o) + T_s \quad (17)$$

where average slot lengths are  $\delta$  for an idle slot,  $\{(\frac{P_s}{P_{tr}})T_s + (\frac{P_{tr} - P_s}{P_{tr}})T_c\}$  for busy slot,  $(T_c + T_o)$  for failed transmission slot and  $T_s$  for successful transmission slot. Since channel is sensed busy when at least one transmission is holding a given time slot, the probability that channel is busy in a time slot is same as probability of successful transmission  $P_{tr}$ .

$$T_o^{basic} = SIFS + T_{ACK\_timeout} \quad (18)$$

$$T_o^{RTS/CTS} = SIFS + T_{CTS\_timeout} \quad (19)$$

We have evaluate the performance of ARB by comparing with existing BEB algorithm through following parameters: initial window size ( $T_{CW}$ ), backoff increasing factor ( $\sigma$ ), and retry limit ( $L_{retry}$ ) for basic access method only due to space limitation.

TABLE II  
SIMULATION AND ANALYTICAL RESULTS (LEGEND:NST,NORMALIZED  
SYSTEM THROUGHPUT(BPS);CAD,CHANNEL ACCESS  
DELAYS(SECOND);N,NUMBER OF ACTIVE REPORTING  
NODES;S,SIMULATION;A,ANALYTICAL;E,RELATIVE ERROR)

NST	S/A	N = 50	N = 100	N = 200	N = 300	N = 400
	S	701360	515964	430202	368480	283290
	A	650260	579680	502340	454700	420300
	E	0.07%	-10.9%	-14.3%	-18.9%	-25.4%
CAD	S	7.349	10.07	11.53	18.33	24.28
	A	6.175	9.11	13.56	17.24	20.56
	E	19%	10.5%	-14.9%	6.32%	18%

## V. SIMULATION & NUMERICAL RESULTS

In this section, we present simulation and Numerical results to evaluate the performance of the proposed ARB. The analytical results were produced by solving non-linear equations of model using MATLAB, then simulations were conducted using ns-2 network simulator [18] to validate the analytical results. All the parameters used in analytical model and our simulations can be found in [2] for DSSS as summarized in Table-I. This paper uses simulation model with similar assumptions as those in analytical model. Lucent's WaveLAN parameters are used for radio model with 250 transmission range and 1 Mb/s channel capacity.

One hundred sensor nodes are randomly located in as area of 1000 m by 1000 m. each node has enough data to send to obtain saturated condition. The number of active reporting nodes that are engaged to report data for an event, can vary to see the performance degradation due to increased collision probability. Using ns-2, The IEEE802.11 simulation module, the DSDV routing module, and UDP transport module had been used to configure the connections among sensor nodes. For proposed ARB algorithm, the DSDV routing protocol and UDP transport module had been used to create traffic connections among sensor nodes. The traffic sources generate constant bit rate (CBR) traffic with the packet size of 1000 bytes at a rate of 2 packets/sec. for simulation time of 300 second. Table-II shows the simulation versus numerical results for proposed ARB algorithm, where the relative error is calculated by  $(Simulation\ Result - Analytical\ Result)/Analytical\ Result$ . As shown in the table, both the results are much satisfactory with minimum errors for normalized system throughput (NST) and channel access delays (CAD).

### A. Effectiveness of proposed ARB algorithm :

Figs.3-5 have results with following parameters for BEB model and proposed ARB model:  $[\sigma_{BEB}, \sigma_{ARB}] = [2, 2]$ ,  $[L_{retry,BEB}, L_{retry,ARB}] = [4, 4]$ ,  $[W_{0,BEB}, T_{CW}] = [32, 16]$ , and  $[CW_{max,BEB}, CW_{max,ARB}] = [1024, 1024]$ . Figs.3-5 show normalized system throughput, Channel access delay and Frame-dropping probability for BEB model and proposed ARB model over the number of active reporting nodes. As shown in Figures, proposed ARB model has better throughput (channel access delay) than that of BEB model of IEEE 802.11 DCF. It is clearly shown that proposed ARB model with initial contention window ( $T_{CW}$ ) and halving contention

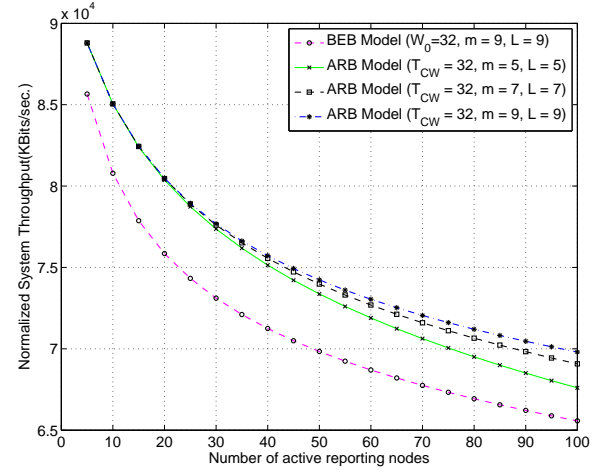


Fig. 3. Normalized System Throughput vs. the number of active reporting nodes

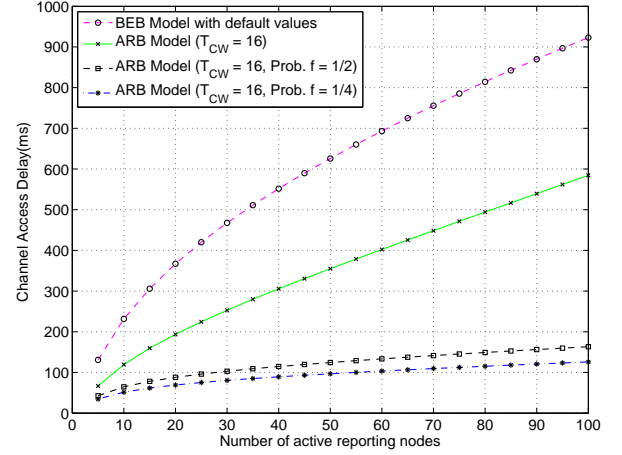


Fig. 4. Channel Access Delay vs. the number of active reporting nodes

window with probability  $f$  after each successful transmission, contributes to further improvement in the performance.

### B. Effects of initial window size ( $T_{CW}$ ) in ARB algorithm:

Figs.6-8 have results with following parameters for proposed ARB model:  $\sigma_{BEB} = 2$ ,  $L_{retry,ARB} = 4$ ,  $CW_{max,ARB} = 1024$ , and  $N = 100$ . Fig.6 and Fig.7 show normalized system throughput, Channel access delays over the initial contention window size ( $T_{CW}$ ) that changes from 4 to 60. As shown in Fig.6 and Fig.7, as the initial contention window ( $T_{CW}$ ) increases the throughput (channel access delay) increases, but larger value of  $T_{CW}$  will increase the number of free slots which causes the channel access delay. The results using proposed ARB model indicate that better throughput (channel access delay) can be achieved with minimum value of initial contention window size ( $T_{CW}$ ). Fig.8 shows that as the initial CW size increases frame-dropping probability decrease. The frame-dropping probability can be minimized by selecting an optimal value of probability  $f$  between  $Prob. f = 1$  and  $Prob. f = 0.5$ .

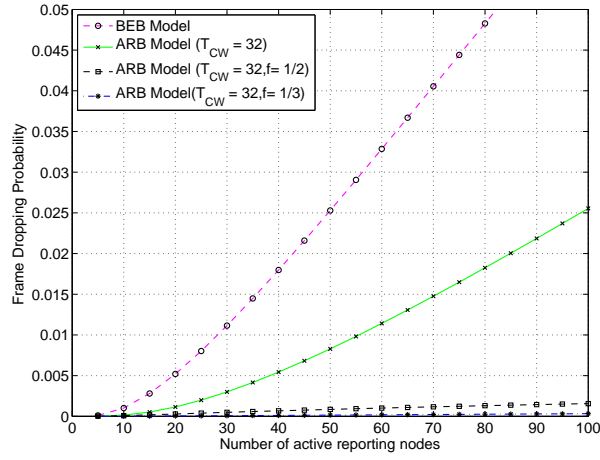


Fig. 5. Frame Dropping Probability vs. the number of active reporting nodes

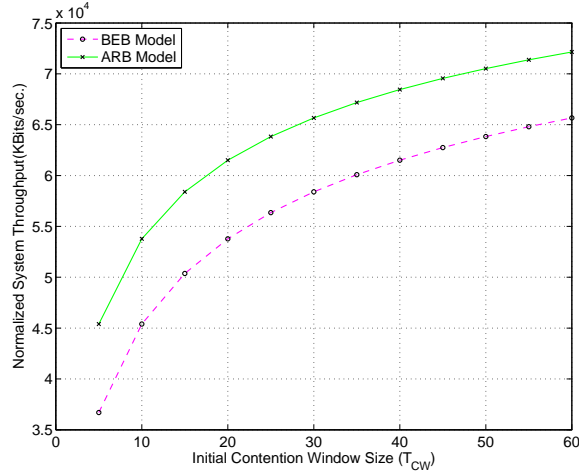


Fig. 6. Normalized System Throughput vs. the initial contention window size ( $T_{CW}$ )

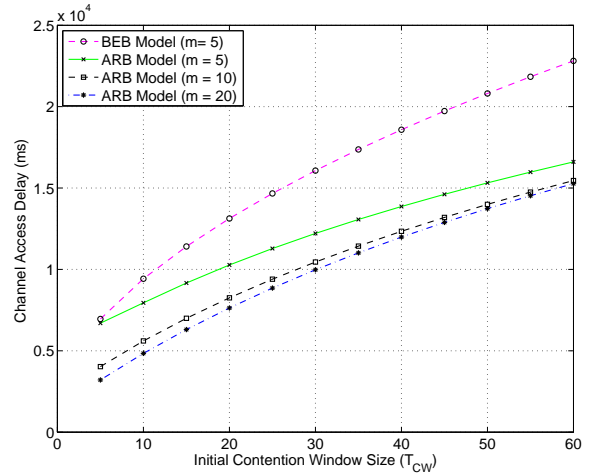


Fig. 7. Channel Access Delay vs. the initial contention window size ( $T_{CW}$ )

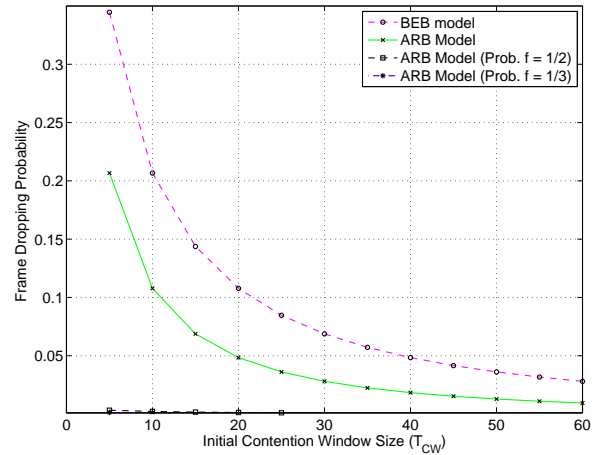


Fig. 8. Frame Dropping Probability vs. the initial contention window size ( $T_{CW}$ )

### C. Effects of halving the CW with probability $f$ in ARB algorithm:

Figs.9-?? have results with following parameters for our ARB model:  $\sigma_{BEB} = 2$ ,  $T_{CW} = 4$ ,  $L_{retry,ARB} = 4$ , and  $CW_{max,ARB} = 1024$ . Fig.9 shows Channel access delays with different probabilities  $f$  over the number of active reporting nodes. After each successful transmission, halving the CW will minimize the new collisions so that proposed ARB model using this enhancement will decrease the channel access delay as the number of active reporting nodes increase.

## VI. CONCLUSIONS

In the design of a backoff algorithm for IEEE 802.11 DCF based event-driven WSN, the contention window size must be adjusted according to the number of reporting nodes of an event which is indication of current network status. So that network performance can be improved to report data of an event into sensor network applications. We have presented and analyzed two enhancements of 802.11 MAC in order to optimize the channel access over event-driven workload. Using Bianchi's analytical model, we analyze the performance

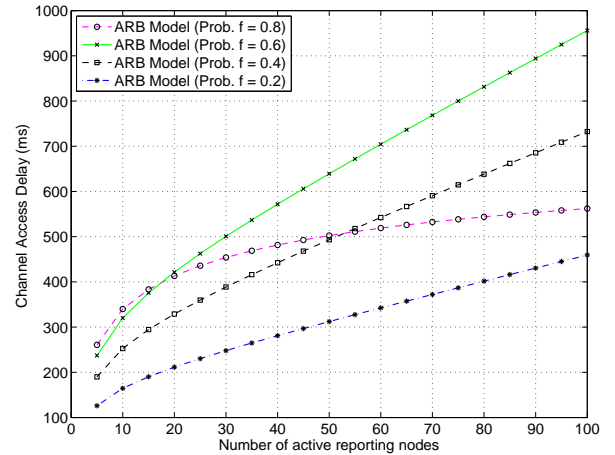


Fig. 9. Channel Access Delay with different probabilities  $f$  over the number of active reporting nodes

of existing BEB and proposed ARB algorithm to obtain network throughput, channel access delay and frame-dropping probability. To validate the analytical results, the simulation results are provided. The results indicate that proposed ARB

algorithm yielded higher network throughput and lower channel access delay than backoff algorithm (BEB) of IEEE 802.11 MAC. These changes could reduce the average number of free slots and collision probability. Our results show that with halving CW according to probability  $f$ , both throughput and latency can be improved with a higher frame-dropping probability.

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